

10/538802

JC09 Rec'd PCT/PTO 13 JUN 2005

IN THE UNITED STATES PATENT & TRADEMARK OFFICE

International Patent Application No.: PCT/DE2003/004129

International Filing Date: 11 December 2003

Paris Convention Priority Date: 13 December 2002

Inventors: Ter-Avetisyan et al.

For: Apparatus and Method of Making a Droplet Target

**English Translation of Applicants' Original German Specification  
Including Their Preliminary Amendment of 13 June 2005  
with Brackets and Underlining**

*Sub  
Spec*



arrangement in a defined manner to set the size of the droplets. In this arrangement the gaseous initial material is converted to a liquid one. Moreover, the droplets interact with the laser very close to the nozzle which in consequence of the heat and erosion is destroyed.

5

In Opt. Common. 103, 105 (1993), L. Ramble and H. M. Hertz report on an X-ray source in which droplets of ethanol are used as the target. To generate these droplets, ethanol was pressed at 30 to 50 at into a vacuum chamber through a capillary of about 10  $\mu\text{m}$  diameter tapering in the direction  
10 of the nozzle. In order to generate a liquid volume - in this case of a diameter of 15  $\mu\text{m}$  - pressure surges were piezo-electrically produced at a frequency of about 1 MHz. The relatively large droplets were used for examining the interaction with laser radiation in an intensity range of  $10^{12}$  to  $10^{14}$  W/cm<sup>2</sup> as described by O. Hemberg, B. A. M. Henson, M. Berlund and H. M. Hertz in J.  
15 Appl. Phys. 88, 5421 (2000). Since in this case each individual droplet is interacting and the laser focus is but slightly larger than the diameter of the droplets of ethanol, the drift problem of the droplet source is of major importance, the project is especially directed to solving an exact droplet-laser synchronization.

20

Super dense droplet spray of a density of up to  $10^{19}$  atoms/cm<sup>3</sup> and a droplet diameter of about 1  $\mu\text{m}$  was produced by a droplet source described by L. C. Mountford, R. A. Smith and M. R. H. R. Hutchinson in Rev. Sci. Instrum. 69, 3780 (1998) and is the basis of the instant invention. The basis  
25 of this droplet source is a magnetic valve which forms the pulse of liquid and, therefore, the volume of the liquid. A receptacle was filled with a liquid and kept under high pressure by means of methanol. The valve is opened in synchronism with the laser pulse and for 2,500  $\mu\text{s}$  to allow droplets to emerge from the nozzle. It was possible to produce droplets of lesser diameter of  
30 about .6  $\mu\text{m}$  by subsequent electrostatic cleaving of the droplets. This, however, requires a technically complex arrangement. However, the jog consisting of such droplets is of lower density, viz. about  $10^{16}$  atoms/cm<sup>3</sup>.

For effectively generating X-rays or EUV light it is necessary, however, to make available droplet targets of dimensions of the size of possible laser wavelengths (T. D. Donnelly, M. Rust, I. Weiner, M. Allen, R. A. Smith, C. A. Steinke, S. Wilks, J. Zweiback, T. E. Cowan, and T. Ditmire, J. Phys. B: At. Mol. Opt. Phys. 34, L313 (2001)) and, therefore, of a smaller diameter compared to the prior art, and which form a spray of an atomic density of  $> 10^{18}$  atoms/cm<sup>3</sup>.

#### OBJECT OF THE INVENTION.

It is thus an object of the invention to provide a way by which such droplet targets can be produced. The high density is also to be realized at a greater distance from the nozzle, i.e., the droplet target, compared to the prior art, is of a superior collimation in order to extend the useful life of the nozzle.

#### SUMMARY OF THE INVENTION.

The object is accomplished with an apparatus of the type referred to *supra* in which the nozzle, in accordance with the invention, is constituted by an supersonic nozzle, the valve is connected to the supersonic nozzle by an expansion channel, heating means are formed around the expansion channel such that the temperature may be set at a level at which a super saturated vapor is generated in the expansion channel, and an insulation is provided between the electromagnetic valve and the heating means.

The invention makes possible the generation of super dense sub- $\mu$  liquid targets required for examining the interaction between laser radiation and plasmas. In contrast to the mentioned prior art generating droplets in the saturated gas phase, the droplets in accordance with the invention are generated from super saturated vapor which condenses into a cloud of spray. The target generated by the apparatus of the invention consists of droplets of an mean diameter of about 150 nm and is of an mean atomic density of  $>$

10<sup>18</sup> atoms/cm<sup>3</sup>. Such a target makes it possible the examination of conditions hitherto not researched which exist between clusters (from several atoms to 10<sup>16</sup> atoms/cluster of a local density approximating that of a solid) and solids. Moreover, relative to the advantages of a cluster target, the  
5 spatial extent of the droplets influences an increased volume charge limitation of hot electrons which, in turn, results in an improved coupling of the laser energy with the ions of the droplets. Thus, a much hotter plasma can be generated and the effect in the X-ray conversion can be improved. The droplet target produced with the device of the invention can be generated  
10 continuously and is of chronologically unlimited operation.

Embodiments of the apparatus in accordance with the invention relate to the structure of their individual components. The pulsed electromagnetic valve operates at a pulse length of 2 ms; the length of the expansion channel  
15 is from several mm to several cm and its diameter is from several 100 μm into the mm range; the supersonic nozzle has a conical opening angle 2Θ from several degrees to several 10°, an input opening of several 100 nm diameter and a conical section of a length of several mm. After pressing the target liquid upon opening of the valve into the expansion channel where as a result  
20 of the heating a supersaturated water vapor is present, it will expand during passage through the ultrasonic nozzle, cool, and form liquid droplets of the desired size and density, the parameters being determined by the dimensions of the expansion channel, its temperature and the prevailing pressure in it.

25 The method in accordance with the invention includes the following method steps: Filling of a target liquid into a container, in which a high pressure is realized by means of a non-reactive gas, brief opening of the receptacle by a pulsed electromagnetic valve, pulsed introduction of the target liquid into an expansion channel, heating of the expansion channel  
30 such that a supersaturated liquid vapor is generated, cooling of the vapor during passage to a supersonic valve connected to the expansion channel, discharge of the droplets from the output opening of the nozzle into a

vacuum.

In some embodiments of the invention a pulsed electromagnet valve is used operating in the ms range and, more particularly, at a pulse duration of 2  
5 ms. At each switching of the valve the target liquid is pressed into the expansion channel and the corresponding vapor is pressed into the supersonic nozzle. An expansion channel of several mm to several cm in length and a diameter of several 100  $\mu\text{m}$  to the mm range and a supersonic  
10 nozzle of with a conical opening angle  $2\Theta$  of several degrees to several  $10^\circ$ , an input opening of several 100  $\mu\text{m}$  diameter and a conically shaped section several mm in length are used. During its passage to the discharge opening of the nozzle the supersaturated gas is cooled in the nozzle. This leads to the formation of liquid droplets. It is further to be mentioned that in addition to the mentioned parameters of the expansion channel the diameter of the nozzle  
15 also determines the diameter of the liquid droplets emerging from the nozzle opening into the vacuum.

Compared to the prior art which constitutes the basis of the invention, the valve in accordance with the invention regulates the direct feeding into an  
20 additionally provided expansion channel in which the target liquid is heated. The thus present supersaturated gas is fed to the discharge opening of the nozzle and cooled which leads to the formation of droplets in the nozzle. By contrast, in the known arrangement, the valve switches the nozzle directly into its closed and open states which substantially lessens the effect on the  
25 formation and extent of the droplets and their collimation.

#### DESCRIPTION OF THE SEVERAL DRAWINGS.

[The invention will hereafter be described in greater detail with  
30 reference to drawings, in which:] –The novel features which are considered to be characteristic of the invention are set forth with particularity in the appended claims. The invention itself, however, in respect of its structure,

construction and lay-out as well as manufacturing techniques, together with other objects and advantages thereof, will be best understood from the following description of preferred embodiments when read in connection with the appended drawings, in which:

5

Fig. 1 schematically depict the structure of an apparatus in accordance with the invention;

Fig. 2 is a curve of the switching pulse of the valve and the associated intensity of the liquid spray generated as a function of time;

10 Fig. 3 is a curve of the width of expansion of the liquid spray in air and in vacuum as a function of the distance from the discharge opening of the nozzle;

Fig. 4 is a curve of the density of the liquid spray as a function of the distance from the discharge opening of the nozzle; and

15 Fig. 5 is a curve of the relative intensity of scattered light measured by CCD.

#### DESCRIPTION OF THE PREFERRED EMBODIMENT.

The apparatus in accordance with the invention for generating a  
20 droplet target is provided with a pulsed electromagnetic valve 1. The valve closes a receptacle (not shown), in which target liquid is maintained at a pressure of 35 bar by gaseous nitrogen. The target liquid may be water, but in principle it may be any other liquid as well. The valve 1 opens and closes at a pulse duration of 2 ms and, in its open phase, discharges water droplets  
25 into an expansion channel 2 of 1 mm diameter and 15 mm length. By means of a heater 3 a temperature of 150 °C is generated in the expansion channel 2. The expansion channel 2 is separated from the valve 1 by an insulator 5. The supersaturated water vapor now present at the end of the expansion channel 2 is now fed through a supersonic nozzle 4. The nozzle 4 has an  
30 opening angle of  $2\Theta = 7^\circ$ , an input opening of 500  $\mu\text{m}$  diameter and a conical section of 8 mm length and generates sub- $\mu$  liquid droplets into the vacuum. A droplet target which can be continuously generated and which makes

possible a chronologically unlimited operation is formed at the discharge opening of the supersonic nozzle 4.

Fig. 2 displays a curve of the switching pulse of the valve and the  
5 associated intensity of the generated liquid spray as a function of time at a distance of 1 mm from the discharge opening of the nozzle. In this measurement during which the radiation generated by a cw He-Ne-laser was directed to and scattered by the droplet target, and the intensity of the scattered radiation at a spacing of 1 mm from the nozzle opening was  
10 determined, the pulse duration of the valve was 2 ms. It can be seen that the major portion of the spray pulse occurs about 1 ms after opening of the valve.

Fig. 3 shows a curve depicting the spread of the liquid spray as a function of distance from the discharge opening of the nozzle in air and in  
15 vacuum. Compared to results known from the prior art, it can be seen that the collimation resulting in accordance with the invention is improved by about 30%.

The spread geometry of the generated cloud of droplet spray may be  
20 defined as  $R = (.32 \pm .32) \times h + r$ , R being the radius of the spray/fog cloud, h being the distance from the supersonic nozzle and r being the radius of the discharge opening of the supersonic nozzle. A zero distance corresponds to the discharge opening of the supersonic nozzle.

Fig. 4 discloses a curve which depicts the dependency of the density of the droplets within the spray as well as the dependency of the mean atomic density in the spray upon the distance from the discharge opening of the nozzle. The measured droplet density varies as regards droplets of a .15  $\mu\text{m}$  diameter from  $(1.6 \pm .5) \cdot 10^{11}$  droplets per cubic centimeter (or a mean  
30 molecular density of  $8 \cdot 10^{16} \text{ cm}^{-3}$ ) at a distance of 20 mm from the discharge opening. At this droplet size this constitutes a droplet density higher by up to three orders of magnitude than in currently described spray droplet source.



This is important for the conversion of irradiated laser energy.

Fig. 5 depicts the measurement data of the scattered light intensity as a function of the viewing angle. The solid line represents the theoretical distribution of the scattered light intensity of particles of a diameter of .15  $\mu\text{m}$ . The correspondence with the measurement data indicates a closer distribution of the droplet sizes than in the prior art so that - unlike in the prior art - there is no need for a droplet size filter and that in this manner the effective droplet density is advantageously increased.

10

15

20

25

30

[Patent Claims] What is claimed is:

1. An apparatus for generating a droplet target comprising at least one  
receptacle for receiving a target liquid in which high pressure is  
5 realized by a non-reactive gas, an electromagnetic valve switching in  
the ms range connected with the receptacle, and a nozzle,  
characterized by the fact that  
the nozzle is structured as a supersonic nozzle (4);  
that the valve (1) is connected to the supersonic nozzle (4) by way of  
10 an expansion channel (2);  
heating means (3) formed around the expansion channel (2) such that  
the temperature can be set at a level at which a supersaturated vapor  
is formed in the expansion channel (2); und  
an insulation (5) is provided between the electromagnetic valve and (1)  
15 and the heating means (3).
2. The apparatus in accordance with claim 1,  
characterized by the fact that  
the pulsed electromagnetic valve (1) operates at a pulse duration of 2  
20 ms.
3. The apparatus in accordance with claim 1,  
characterized by the fact that  
the length of the expansion channel (2) is from several mm to several  
25 10 mm and that its diameter is from several 100  $\mu\text{m}$  to a range of mm.
4. The apparatus in accordance with claim 1,  
characterized by the fact that  
the supersonic nozzle (4) has a conical opening angle  $2\Theta$  of several  
30 degrees to several 10 degrees, an input opening of a diameter of  
several 100  $\mu\text{m}$  and a conically shaped section of a length of several  
mm.

5. A method of generating a droplet target, comprising the method steps of:
- filling a target liquid into a receptacle in which a high pressure is realized by a non-reactive gas;
  - 5 - brief opening of the receptacle by a pulsed electromagnetic valve;
  - pulsed feeding of the target liquid into an expansion channel;
  - heating the expansion channel such that a supersaturated liquid vapor is generated;
  - 10 - cooling the gas during its passage to a supersonic nozzle connected to the expansion channel; and
  - discharging liquid droplets through the discharge opening of the nozzle.
- 15 6. The method in accordance with claim 5, in which a pulsed electromagnetic valve with a pulse duration in the ms range, in particular 2 ms, is used.
7. The method in accordance with claim 5, in which
- 20 an expansion channel of a length of from several mm to several 10 mm and a diameter of from several 100  $\mu$ m to the range of mm is used.
8. The method in accordance with claim 5, in which a supersonic with a conical opening angle  $2\Theta$  of several degrees to several
- 25 10 degrees, an input opening of a diameter of several 100  $\mu$ m and a conically shaped section of a length of several mm is used.]
9. (New) An apparatus for generating a droplet target, comprising:
- at least one receptacle for receiving a target liquid and adapted to have
  - 30 its interior maintained under high pressure;
  - an electromagnetic valve switching between open and closed states by pulses in the range of ms;

means for feeding target liquid to the valve from the receptacle;  
a supersonic nozzle;  
an expansion channel for feeding target liquid from the valve to the  
nozzle;

5 heating means associated with the expansion channel for converting  
target liquid therein to supersaturated vapor by a predetermined temperature;  
and

insulating means between the electromagnetic valve and the heating  
means.

10

10. (New) The apparatus of claim 9, wherein the pressure is maintained by  
a non-reactive gas.

11. (New) The apparatus of claim 10, wherein the non-reactive gas is  
15 nitrogen.

12. (New) The apparatus of claim 9, wherein the predetermined  
temperature is about 150 °C.

20 13. (New) The apparatus of claim 9, wherein the duration of the pulses is 2  
ms.

14. (New) The apparatus of claim 9, wherein the expansion channel is of a  
length from between several mm and several 10 mm and of a diameter of  
25 from several 100 µm into the range of mm.

15. (New) The apparatus of claim 14, wherein the length is 15 mm and the  
diameter is 1 mm.

30 16. (New) The apparatus of claim 9, wherein the supersonic nozzle is  
provided with a conical opening angle  $2\Theta$  of from several degrees to several  
10 degrees, an input opening of several 100 µm diameter and a conically

shaped section of a length of several mm.

17. (New) The apparatus of claim 16, wherein the opening angle is  $7^\circ$ , the diameter is 500  $\mu\text{m}$  and the length of the conically shaped section is 8 mm.

5

18. (New) A method of making a droplet target, comprising the steps of:  
filling a receptacle with a target liquid;  
maintaining a predetermined pressure within the receptacle;  
briefly opening the receptacle by means of a pulsed electromagnetic

10 valve;

feeding the target liquid through the electromagnetic valve into an expansion channel;

heating the expansion channel to a temperature sufficient to convert the target liquid into a supersaturated vapor;

15 feeding the supersaturated to a supersonic nozzle;

cooling the supersaturated vapor passing to the nozzle to condense to droplets; and

discharging the droplets from the nozzle.

20 19. (New) The method of claim 18 wherein the pressure is maintained by gaseous nitrogen at 35 bar and the valve is pulsed at 2 ms.

20. (New) The method of claim 18, wherein the supersaturated vapor is fed to an expansion channel of a length of from several mm to several 10 mm

25 and a diameter of from several 100  $\mu\text{m}$  to the range of mm.

21. (New) The method of claim 18, wherein the supersaturated vapor is fed into and is cooled in a supersonic nozzle having a conical opening angle  $2\Theta$  of from several degrees to several 10 degrees and a conically shaped

30 section of a length of several mm.

[Abstract] ABSTRACT OF THE DISCLOSURE.

[In order to effectively generate x-rays or EUV light, droplet targets must be available, which form a fog having an atomic density of  $> 10^{18}$  atoms/cm<sup>3</sup> while the dimension thereof ranges within potential wavelengths of laser beams, i.e. the diameter thereof is smaller than diameters known in prior art. The aim of the invention is to offer a solution for creating such droplet targets while the high density is to be created at a greater distance from the nozzle, i.e. the droplet target is to collimate better than in prior art in order to extend the service life of the nozzle. Said aim is achieved by a device at least comprising a receptacle which receives a target liquid and inside which a high pressure is generated by means of a non-reactive gas, an electromagnetic valve that is connected to the receptacle and switches in the millisecond range, and a nozzle. Said nozzle is embodied as a supersonic nozzle to which the valve is connected via an expansion channel. Heating means that are disposed around the expansion channel are configured such that the temperature is adjustable to a level at which an supersaturated vapor is formed inside the expansion channel, an insulator being arranged between the electromagnetic valve and the heating means. The inventive device allows highly dense liquid targets in the sub- $\mu$  range to be created.]

An apparatus for making a droplet target provided with a chamber for receiving a target liquid and maintained under pressure, an electromagnetic valve switched at a ms rate for feeding target liquid from the receptacle to a heated expansion channel for converting the target liquid to supersaturated vapor and connected to a supersonic nozzle wherein the supersaturated vapor is cooled and condensed to droplets before they are discharged.